

# Comparison of Optimization Algorithms for Contracted Capacity of Power Consumer with Self-Owned Generating Units

<sup>1</sup>Hong-Tzer Yang, <sup>2</sup>Pai-Chun Peng

<sup>1</sup>Department of Electrical Engineering, National Cheng Kung University, Tainan City, Taiwan

<sup>2</sup>Department of Electrical Engineering, Chung-Yuan Christian University, Chung Li City, Taiwan

Emails: htyang@mail.ncku.edu.tw; g9302803@cycu.edu.tw

## Abstract

Contracted capacity setting is a discrete and nonlinear optimization problem in consideration of expenses on the electricity from the utility and costs of the self-owned generating units (SOGUs) at the same time. This paper analyzes and compares the proposed improved Taguchi method and the cultured differential computation algorithm (CDCA) in solving this problem. The improved Taguchi method provides fast converging characteristics in searching the optimal solution through quality analysis in orthogonal matrices. The cultural algorithm (CA) used in the CDCA extracts and saves the domain knowledge or problem properties during the evolution process. The differential computation of the CDCA provides fast converging characteristics in searching the optimal solution through operations of mutation, crossover, and selection operations, which are efficient and different from the existing generic algorithm (GA). To compare the proposed methods, the paper employs the real data obtained from an optoelectronics factory in Taiwan. In comparison with the existing optimization methods in different optimization problems, the proposed approaches have superior results as revealed in the numerical results with respect to the computation time and the solution quality.

## Keywords

*Self-Owned Generating Units; Optimal Contracted Capacity; Cultured Differential Computation Algorithm*

## Introduction

To determine the contracted capacity and the operation scheduling of the SOGUs is a highly discrete and nonlinear optimization problem. The discrete feature arises from the utility time-of-use (TOU) tariff designs for different peak, semi-peak, and off-peak periods of power consumption and the penalty for excessive load over contract, as well as the adjusting fees of contracted capacities. The nonlinear characteristics results from the operation dispatch of

the SOGUs with nonlinear cost functions. A lot of approaches have been adopted in the literature to solve such a discrete and nonlinear optimization problem and some of them [1]-[9] are discussed below.

In the nonlinear cost minimization problem for operation of a generation system, heuristic translation method [1] to determine the contracted capacities is suggested and widely used by Taiwan Power Company (TPC). Because of its use only in determination of the contracted capacity, the method cannot solve the nonlinear problem with the operations of SOGUs considered. Alternatively, to solve the similar optimization problems for operations of an energy supply system, mixed integer programming techniques have been used [2], [3] and the contracting policies for energy purchase/sale under liberalized energy markets [4]-[8] with promising results obtained in the studies. The framework, cost influence, optimal purchase in the demand bidding problem are further reviewed in [8] for the bidding strategy in a day-ahead market of a large consumer. More information can be found in [9] on the electricity procurement strategy in a day-ahead market and a subsequent adjustment market.

The genetic algorithm (GA), the evolutionary programming (EP), and the Taguchi or improved Taguchi approaches have also been used to solve various optimization problems in power and energy systems [10]-[13], the contracted capacities setting problems [14], [15] for industrial customers with/without consideration of the SOGUs, which complicates the optimization problem. Required for the evolutionary computing for the capacity contract determination problem are the long searching time, the parents tuning effects, and the quality of the

solution searched, especially for the problem with SOGUs taken into account in this paper. The Taguchi or the proposed improved Taguchi approaches in [16] and [17], respectively, may enhance the global and local exploration abilities with good flexibility. However, the complex design for the orthogonal matrix included in the quality analysis may decrease the efficiency and the quality of outcome.

The proposed approach of CDCA [18] may effectively search the best combination of contracted capacities and dispatch output of SOGUs. The Taguchi based method proposed by the authors in [17] for the optimal contracted capacity determination can thus be further ameliorated. In the proposed CDCA, the differential evolution (DE) [20] provides fast converging characteristics in searching the optimal solution through operations of mutation, crossover, and selection operations. The operations are efficient and different from the existing GA. The CA [18]-[21] in the CDCA incorporates domain knowledge or problem properties obtained during the evolution process to make the search process more efficient.

In this paper, we have employed real data collected from supervisor control and data acquisition (SCADA) system of an optoelectronics factory with SOGUs in Taiwan and the practical Taiwan power system for the comparisons. The obtained simulation results demonstrate the feasibility and effectiveness of the proposed method in terms of convergence speed and solution precision compared with the heuristic scheme [1], GA [22], the mixed-integer linear program (MILP) [2], the improved Taguchi optimization [17], and the CDCA method [18].

### Problem Formulation

In this section, the current tariff structure of TPC is mathematically expressed with cost function of SOGUs (Please also refer to [17]) to clarify the discrete and nonlinear nature of the problem mentioned before.

In the current tariff structure of TPC, the electricity bill of its customers is composed of the fees for capacity ( $B_j$ ), energy ( $S_j$ ), regulated power factor ( $R_j$ ), excessive load over the contracted capacities ( $F_j$ ), and contracted capacity ( $C_j$ ). The operation costs of the SOGUs consist of fixed and variable costs ( $C_j^{\text{SOGUs}}$ ). Since the SOGUs are assumed to have been invested and installed, the fixed costs would not affect the decision of the contracted capacity and the operations of SOGUs, only given here are the operation costs of

the SOGUs. On the other hand, suppose the consumer has the possibility of selling its excess energy ( $R_s$ ).

To avoid over-capacity penalty, auxiliary power sources of SOGUs are often used to supply the load demand exceeding the contracted capacity with extra operating costs. Therefore, an optimal contracted capacity exists with minimal total expenses of power consumption. The contracted capacity would determine the power expenses to pay the utilities and the related operating costs of the SOGUs. In this paper, by considering the expenses on the utility power and the operating costs of the SOGUs, the objective function of the optimization problem is formulated as in Eq.1.

$$\text{Min} \{J_T\} = \sum_{j=1}^M B_j + S_j + R_j + F_j + C_j + C_j^{\text{SOGUs}} - R_s \quad (1)$$

where  $J_T$  is the total power expenses of the consumer with SOGUs for the  $M$ -month planning horizon. As shown in Eq.1, the total power expenses  $J_T$  of the consumer with SOGUs include the capacity fee ( $B_j$ ) and energy fee ( $S_j$ ) in Eq.15 and Eq.18, respectively, depending on the capacities contracted with the utilities and the actual energies consumed by the consumer during different periods. Besides, as failing to keep the power factor above 0.8 or consuming the power exceeds the contracted capacity, the consumer has to pay for the power factor penalty ( $R_j$ ) and excessive load penalty ( $F_j$ ) thus incurred based on Eq.19 and Eq.24, respectively. To meet different load levels, adjusting the contract capacities would also cause the adjusting fees ( $C_j$ ) in Eq.29. Plus, the operating costs of the SOGUs ( $C_j^{\text{SOGUs}}$ ) in Eq.35 should be taken into account due to its operations to compensate for the power demands to avoid the penalty for excessive load ( $F_j$ ). Without loss of generality, the sold excess energies generated by the SOGUs are considered in the last term  $R_s$  of Eq.37.

The detailed description of the items in Eq.1 can be referred to Section 6, [17] and [1], where the discrete and nonlinear nature of the problem can be clearly observed.

### Overviews of Compared Methods

In this section, we briefly describe referenced existing optimization methods, GA, PSO-integrated Taguchi method, and CDCA to solve the contracted capacity optimization problem of the power consumer with SOGUs.

### The GA Method

In the conventional GA, for genetic operations of selection, crossover, and mutation, usually used is the binary-string coding to represent a solution for further evolution [11]. The size of a population is, therefore, the number of binary strings. In the optimal contracted capacity problem, an integer, serving to represent a solution of contracted capacity, is used directly in a string for the operations of GA.

#### 1) Initialization and Selection

For a given population size  $N_{P\_GA}$ , a set of initial  $N_{P\_GA}$  integer strings are created. An integer in the string is obtained randomly. The operator of Roulette-wheel selection is used. A string is selected from the current population to the next according to the probability given by:

$$\text{Prob}(U_{GA\_j}^{GA\_g}) = \frac{F_{GA}(U_{GA\_j}^{GA\_g})}{\sum_{j=1}^{N_{P\_GA}} F_{GA}(U_{GA\_j}^{GA\_g})} \quad (2)$$

where  $U_{GA\_j}$  is the  $j$ th string of the current population,

$N_{P\_GA}$  is the size of population,

$GA\_g$  is the number of iteration,

$F_{GA}(U_{GA\_j})$  represents the fitness value of  $U_{GA\_j}$ .

As indicated in (2), evaluated are the probabilities of the strings of the current population to survive in the next population based on their fitness. On the basis of the probabilities evaluated in (2), the roulette wheel strategy [11] is used for the random selection.

#### 2) Arithmetic Crossover

In the GA, the crossover algorithm is employed as an arithmetic operator [11]. For each string selected through (2), arithmetic crossover operator is used as follows for each string in the population.

$$\begin{aligned} U_{GA\_j}^{GA\_g+1} &= (1-\gamma)U_{GA\_select 1}^{GA\_g} + \gamma U_{GA\_select 2}^{GA\_g} \\ U_{GA\_j}^{GA\_g+1} &= \gamma U_{GA\_select 1}^{GA\_g} + (1-\gamma)U_{GA\_select 2}^{GA\_g} \end{aligned} \quad (3)$$

where  $\gamma$  is constant between  $[0, 1]$ .

#### 3) Mutation

The strings of the new population after selection and crossover are evolved through the mutation operator with geometric mean probability [11]. It also reveals that the mutation probability function defined in [11] ensure the diversity of the searching directions as the

population evolves to the optimal solution. The solution trapped in the local optimum can thus be avoided.

### The PSO-Integrated Taguchi Method

As described conventional Taguchi method [16], [17], for each experiment, a solution of controlled variables (i.e. the contract capacities) is obtained for evaluation. Through the formulated orthogonal matrix, quality analysis on the particles of a population is performed with the costs and contribution values derived from the matrix for the iteration  $g$ . In the PSO-integrated Taguchi method [17], the particle is defined as a vector of the input levels of controlled variables to be determined as follows.

$$P_g^{(i)} = [p_{1,g}^{(i)}, \dots, p_{n,g}^{(i)}, \dots, p_{N,g}^{(i)}] \quad (4)$$

where  $i = 1, \dots, q$  and  $n = 1, \dots, N$ ,

$N$  is the number of controlled variables,

$q$  is the number of input levels as defined in the orthogonal matrix [16].

As noted,  $q$  is also the number of particles employed in the PSO algorithm for a population in a generation or iteration. Given the population of particles, the orthogonal matrix  $L_v(q^N)_g$  can thus be formulated according the creation rules[16], [17]. It is noted that an orthogonal matrix  $L_v(q^N)_g$  corresponds to a generation of PSO in searching the optimal solution based on the contribution values with integrating the PSO method.

### The CDCA Method

The cultural algorithms are evolutionary methods that extract information of the domain of the problem during the evolutionary process itself. A cultural algorithm contains two main parts: the population space, and the belief space. The population space consists of a set of possible solutions to the problem, and can be modeled using any population based technique, e.g. genetic algorithms.

The DE [20] is a parallel direct search method with good convergence properties. Differential evolution is based on a mutation operator, which adds an amount obtained by the difference of two randomly chosen individuals of the current population. Through the arithmetic operators, such as mutation, crossover, and selection, the DE technique can find the optimal

solution from vectors of decision variables.

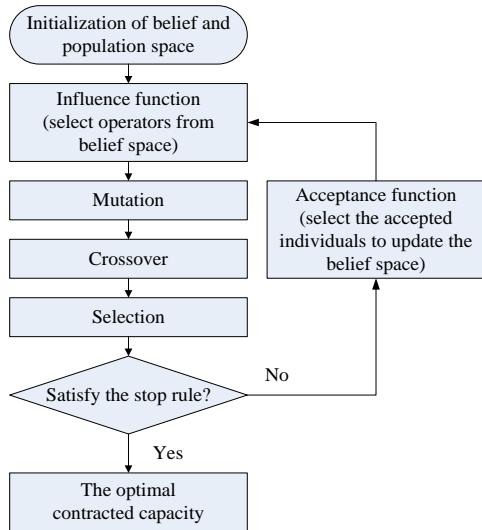


FIGURE 1 FLOWCHART OF THE PROPOSED CDCA

The proposed CDCA in [18] for the contracted capacity optimization uses the DE described above and integrates four control knowledge sources into the population space and the belief space of CA. Four control knowledge sources are employed in the belief space: situational, normative, topographical, and historical knowledge sources. The communication protocol is used to communicate between the belief and population spaces via acceptance and influence functions. The detail formulations are shown in [18].

The solution structure of the proposed CDCA is delineated in **Figure 1**. With the belief and population spaces initialized, the influence function selects the mutation operations based on the four knowledge sources. Among the new population generated, the acceptance function then selects the individuals from the population space. The knowledge thus acquired is then used to update the belief space by determining the number of accepted individuals and the probability of the four knowledge sources to be applied to the next DE process. The evolutionary process terminates according to the given maximal number of generations.

## Numerical Results

To compare and verify the effectiveness of the existing and proposed methods, the methods are numerically tested the contract capacity determination problems.

### Description of the Test Systems

In this paper, the real data obtained from the SCADA system of a large optoelectronics factory with SOGUs

in September, 2004 to March, 2005 were used. Based on their experiences, the load demand in this example can be regarded as deterministic. The case studies serve to investigate the effectiveness of the proposed method in the optimization of the contract capacities. Besides, since the consumer did not have the contract with the utilities as an IPP (independent power producer) to sell the energy, it was supposed there was no energy sold in the case studies.

The data used include the operation costs of the SOGUs, the predicted power load demands, and the power bills from the utilities. Total seven SOGUs had been installed with maximum power output of 8MW for each. Through these methods, the optimal solution of the contracted capacities, the consumption of the power from utilities, and the total electrical power expenses are obtained. The algorithm was run in a personal computer of Pentium-4 with 3.0GHz CPU and 512MB RAM.

### Testing Results

We analyze the solution quality and the efficiency, as well as the converging speed for performance comparison of the proposed and the existing methods described as follows.

Method 1. Use the heuristic translation method [1] to determine the contracted capacities and the operations of SOGUs (the solution) as adopted the factory currently,

Method 2. Use the GA [22] approach to determine the solution,

Method 3. Use the MILP method [2],

Method 4. Use the improved Taguchi method [17],

Method 5. Use the CDCA method as proposed in this paper.

The results shown in **Figure 2** are the comparison results of the total electrical power expenses for the total load demand of 276,939,539kWh during the seven-month planning horizon in different methods. The solution obtained from the proposed CDCA approach for the case of without SOGUs (Method 1) shows that the total power expenses are higher than all the solutions with SOGUs added.

It is noted that though the fixed costs of the SOGUs are not shown in the paper, the costs of depreciation were taken into consideration in all the evaluations. As compared to the heuristic translation method [1]

adopted by the factory currently, the numerical results show that the GA [22], MILP [2], and the improved Taguchi [17] methods may achieve very close cost reductions of 10.27%(or US\$1.5 million), 10.20%(or US\$1.49 million), and 12.18%(or, respectively, as given in **Table 1**. Through the proposed CDCA approach, saved is about US\$2.1

million or 14.56% of the total electrical power expenses for the seven months under consideration. It reveals that by implementing the proposed optimization approach in determining the contracted capacities and operations of the SOGUs during different periods, electricity expenses can be significantly saved.

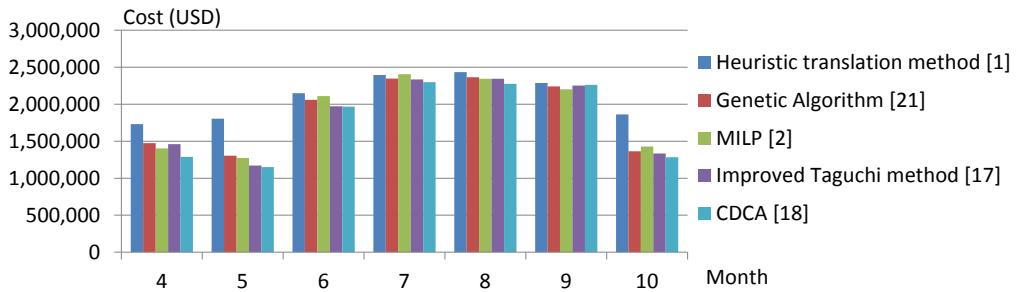


FIGURE 2 COMPARISONS OF THE CONTRACT CAPACITIES IN EACH MONTH FOR DIFFERENT APPROACHES

TABLE 1 COMPARISONS OF THE TOTAL EXPENSES AND COST SAVINGS FOR DIFFERENT APPROACHES

Method	Heuristic translation method [1]	Genetic Algorithm [22]	MILP [2]	Improved Taguchi method [17]	CDCA [18]
Power consumption from SOGUs (kWh)	28,870,409	23,051,099	43,343,658	94,275,541	61,699,477
Ratio (%)	10.42	8.32	15.76	34.29	22.28%
Total expenses (US\$)	14,658,627	13,153,360	13,163,367	12,872,942	12,524,258
Cost Savings (%)	0%	10.27%	10.20%	12.18%	14.56%

## Conclusion

In this paper, the proposed optimization approaches have been proposed for determination of the contracted capacity. From the practical numerical results, the proposed CDCA approach, as compared with the heuristic method currently adopted by the factory, may save up to 14.56% of electrical power expenses in total. Also, in comparison with the existing optimization methods, such as the GA, MILP, and the improved Taguchi based optimization approaches, the proposed CDCA method has superior results as revealed in the numerical results in terms of the computation time needed and the quality of solution obtained.

It is interesting to note from the obtained numerical results that the case without the SOGUs included had higher total power expenses as compared with the cases with SOGUs. The reason may arise from the short planning period (seven months) considered only, while the capital investments of the SOGUs and their infrastructures are depreciated into 20 years and leveled into each month in the current studies. Further, though no excess energy sold was assumed due to the regulation structure of the Taiwan power

system, the proposed approach can be well applied to the cases with the selling of excess energy taken into account.

## Appendix

As mentioned in Section 2, the electricity expenses of the consumer for the electricity from the utilities can be expressed, respectively, in the following subsections, which are quoted from [17].

(1) *Capacity Fees ( $B_j$ )*: The fees for the contract capacity ( $B_j$ ) consist of those for regular and reserve capacities, as given below.

$$B_j = B_{j,1} + B_{j,2} \quad (5)$$

where

$$B_{j,1} = \begin{cases} Y_{j,1} \times X_{j,1}, & \text{for } (X_{j,2} + X_{j,3}) - X_{j,1} < 0 \\ Y_{j,1} \times X_{j,1} + (Y_{j,2} \text{ or } Y_{j,3}) \times [(X_{j,2} + X_{j,3}) - X_{j,1}], & \text{otherwise} \end{cases} \quad (6)$$

$B_{j,1}$  is the regular capacity tariff in  $j^{\text{th}}$  month;  $Y_{j,1}$ ,  $Y_{j,2}$ , and  $Y_{j,3}$  are the tariffs of the peak, semi-peak, and off-peak regular capacities, respectively, in  $j^{\text{th}}$  month;  $X_{j,1}$ ,  $X_{j,2}$ , and  $X_{j,3}$  are the corresponding contract capacities in  $j^{\text{th}}$  month. The 1<sup>st</sup> case of Eq.6

illustrates that if the sum of semi-peak and off-peak contract capacities  $X_{j,2} + X_{j,3}$  is smaller than the peak contract capacity, only needed to pay is the fees of peak contract capacity. It is also noted since in the current tariff structure  $Y_{j,2} = Y_{j,3}$ , either  $Y_{j,2}$  or  $Y_{j,3}$  is used in the 2<sup>nd</sup> case of Eq.6.  $B_{j,2}$  is the fees for reserve capacity, and

$$B_{j,2} = B_{j,1} \times 0.15 \quad (7)$$

(2) *Energy Fees ( $S_j$ )*: The energy fees ( $S_j$ ) are based on the real power consumption in different periods.

$$S_j = Y_{j,4} \times Z_{j,1} + Y_{j,5} \times Z_{j,2} + Y_{j,6} \times Z_{j,3} + Y_{j,7} \times Z_{j,4} \quad (8)$$

where  $Y_{j,4}$ ,  $Y_{j,5}$ ,  $Y_{j,6}$ , and  $Y_{j,7}$  are the tariffs of peak, semi-peak, off-peak, and Saturday semi-peak energy consumptions in  $j^{\text{th}}$  month, which are the tariffs determined and announced by the utilities;  $Z_{j,1}$ ,  $Z_{j,2}$ ,  $Z_{j,3}$ , and  $Z_{j,4}$  are the corresponding energy consumptions in  $j^{\text{th}}$  month.

(3) *Regulated Power Factor Expenses ( $R_j$ )*: To regulate the power factor, the consumers whose average power factors are lower than 0.8 have to pay the penalties for low power factors. In contrast, those with higher power factors are rewarded. The formula used for the penalty and reward are stated as follows.

$$R_j = \begin{cases} (B_j + S_j) \times 0.003 \times (0.8 - pf_j), & pf_j \leq 0.8 \\ (B_j + S_j) \times 0.0015 \times (0.8 - pf_j), & pf_j > 0.8 \end{cases} \quad (9)$$

where  $pf_j$  is the average power factor of the consumer in  $j^{\text{th}}$  month.

$$F_{j,2} = \begin{cases} 0, & \text{for } (O_{j,2} - O_{j,1}) \leq 0 \\ 2Y_{j,2} \times (O_{j,2} - O_{j,1}), & \text{for } 0 < (O_{j,2} - O_{j,1}) < 0.1 \times X_{j,2} \\ 3Y_{j,2} \times [(O_{j,2} - O_{j,1}) - 0.1 \times X_{j,2}], & \text{for } (O_{j,2} - O_{j,1}) > 0.1 \times X_{j,2} \end{cases} \quad (12)$$

$$F_{j,3} = \begin{cases} 0, & \text{for } O_{j,3} - \max(O_{j,1}, O_{j,2}) \leq 0 \\ 2Y_{j,3} \times [O_{j,3} - \max(O_{j,1}, O_{j,2})], & \text{for } 0 < O_{j,3} - \max(O_{j,1}, O_{j,2}) < 0.1 \times X_{j,3} \\ 3Y_{j,3} \times \{[O_{j,3} - \max(O_{j,1}, O_{j,2})] - 0.1 \times X_{j,3}\}, & \text{for } O_{j,3} - \max(O_{j,1}, O_{j,2}) > 0.1 \times X_{j,3} \end{cases} \quad (13)$$

$$E_{j,1} = \sum_{t=1}^3 \begin{cases} 0, & \text{for } X_{j,t} \leq X_{j-1,t} \\ P_1 \times [X_{j,t} - X_{j-1,t}], & \text{for } X_{j-1,t} < X_{j,t} \leq \max_{i=1, \dots, j-1} (X_{i,t}) \\ P_1 \times [\max_{i=1, \dots, j-1} (X_{i,t}) - X_{j-1,t}], & \text{for } X_{j,t} > \max_{i=1, \dots, j-1} (X_{i,t}) \end{cases} \quad (15)$$

$$E_{j,1} = \sum_{t=1}^3 \begin{cases} 0, & \text{for } X_{j,t} \leq X_{j-1,t} \\ 0, & \text{for } X_{j-1,t} < X_{j,t} \leq \max_{i=1, \dots, j-1} (X_{i,t}) \\ P_1 \times [X_{j,t} - \max_{i=1, \dots, j-1} (X_{i,t})], & \text{for } X_{j,t} > \max_{i=1, \dots, j-1} (X_{i,t}) \end{cases} \quad (16)$$

$$K_{j,1} = \sum_{t=1}^3 \begin{cases} 0, & \text{for } X_{j,t} \leq X_{j-1,t} \\ P_2 \times [H_j \times X_{j,t} - (X_{j-1,t} + X_{j-2,t} + \dots + X_{j-H_j,t})] - (K_{j,1,1} + K_{j,2,1} + \dots + K_{j-H_j,1}), & \text{for } X_{j-1,t} < X_{j,t} \leq \max_{i=1, \dots, j-1} (X_{i,t}) \\ P_2 \times [H_j \times \max_{i=1, \dots, j-1} (X_{i,t}) - (X_{j-1,t} + X_{j-2,t} + \dots + X_{j-H_j,t})] - (K_{j,1,1} + K_{j,2,1} + \dots + K_{j-H_j,1}), & \text{for } X_{j,t} > \max_{i=1, \dots, j-1} (X_{i,t}) \end{cases} \quad (17)$$

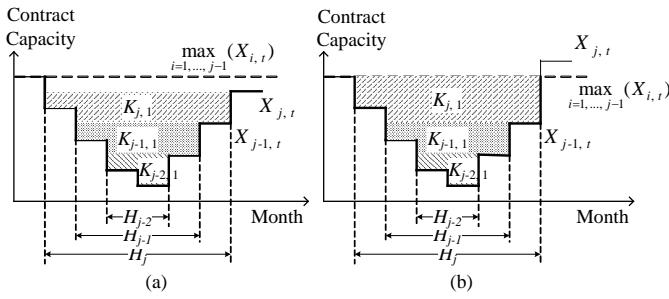


FIGURE 1 SEVERAL EXAMPLES ILLUSTRATING THE ADJUSTING FEES OF THE CONTRACT RESERVE CAPACITY [17]

Based on the descriptions above, the penalty for excessive loads is expressed as in Eq.14.

$$F_j = F_{j,1} + F_{j,2} + F_{j,3} \quad (14)$$

(5) *Adjusting Fees of Contract Capacity ( $C_j$ ):* Based on the original contract capacities with the TPC, the consumers can adjust the contract capacities by paying adjusting fees, except free adjustment of reducing the contract capacity or shifting the peak contract capacity to the off-peak one [1]. The adjusting fees for the increased contract capacities can be divided into two parts comprising the equipment expansion fees  $E_{j,1}$  and  $E'_{j,1}$ , and the equipment maintenance fees  $K_{j,1}$  for transmission and distribution (T&D) systems.

Suppose  $X_{j,t}$  is the adjusted contract capacity from  $X_{j-1,t}$ , where  $t = 1, 2$ , and  $3$  refer to the periods of the peak, the semi-peak, and the off-peak, respectively. The calculations of  $E_{j,1}$  and  $E'_{j,1}$ , as well as  $K_{j,1}$  are given in Eqs.15-17, where  $P_1$  and  $P_2$  are the unit prices of the equipment expansion and maintenance fees, respectively;  $\max_{i=1,...,j-1}(X_{i,t})$  is the

consumer has ever had before for month  $i=1, \dots, j$ . While  $X_{j,t} \leq \max_{i=1,...,j-1}(X_{i,t})$ , only would  $E_{j,1}$  be paid, otherwise both  $E_{j,1}$  and  $E'_{j,1}$  should be paid for the portions with the adjusted contract capacity  $X_{j,t}$  smaller and larger than the previous maximal contract capacity  $\max_{i=1,...,j-1}(X_{i,t})$ , respectively. Separate calculations of  $E_{j,1}$  and  $E'_{j,1}$  are due to different fees for the portions of adjustments lower or higher than  $\max_{i=1,...,j-1}(X_{i,t})$ .

The equipment maintenance fees  $K_{j,1}$  are calculated as shown in Eq.17 where  $H_j$  is the number of months for which the contract capacity  $X_{j-H_j,t}$  is smaller than but next in value to the adjusted capacity  $X_{j,t}$  in month  $j$ , i.e.

$X_{j,t} > X_{j-H_j,t} > X_{j-i,t}$ ,  $i=1, 2, \dots, H_j$ . The instances in

**Figure 3(a) and (b)**, respectively, show the definitions of  $K_{j,1}$  in Eq.17 for cases of  $X_{j-1,t} < X_{j,t} < \max_{i=1,...,j-1}(X_{i,t})$  and  $X_{j,t} > \max_{i=1,...,j-1}(X_{i,t})$ . The shaded areas in **Figure 3(a)** and (b) indicate the ways how  $K_{j,1}$ ,  $K_{j-1,1}$ , and  $K_{j-2,1}$ , for  $H_j = 2$  and  $t = 1$ , are calculated.

In addition to the adjusting fees for contract capacities,  $E_{j,2}$ ,  $E'_{j,2}$ , and  $K_{j,2}$  of contract reserve capacities, should be paid, which are defined in Eq.18.

$$\begin{aligned} E_{j,2} &= 0.25 \times E_{j,1} \\ E'_{j,2} &= 0.5 \times E'_{j,1} \\ K_{j,2} &= 0.15 \times K_{j,1} \end{aligned} \quad (18)$$

According to variation amount of the contract capacity, the adjusting fees  $C_j$  are calculated based on the T&D equipment expansion and maintenance fees of the contract capacity  $C_{j,1}$  and the fees of the reserve contract capacity  $C_{j,2}$ , i.e.

$$C_j = C_{j,1} + C_{j,2} \quad (19)$$

where  $C_{j,1}$  is composed of the equipment expansion and maintenance fees as described in Eq.20 [1].

$$C_{j,1} = \begin{cases} K_{j,1} + E_{j,1}, & K_{j,1} \leq 0.5 \times E_{j,1} \\ 0.5 \times E_{j,1} + E'_{j,1}, & \text{otherwise} \end{cases} \quad (20)$$

Similarly,  $C_{j,2}$  is calculated below.

$$C_{j,2} = \begin{cases} K_{j,2} + E'_{j,2}, & K_{j,2} \leq E_{j,2} \\ E_{j,2} + E'_{j,2}, & \text{otherwise} \end{cases} \quad (21)$$

(6) *Operation Costs of the SOGUs ( $C_j^{\text{SOGUs}}$ ):* The operation costs of the SOGUs consist of fixed and variable costs. Since the SOGUs are assumed to have been invested and installed, the fixed costs would not affect the decision of the contract capacity and the operations of SOGUs, only given here are the operation costs of the SOGUs. The operation costs of generating units comprise the fuel costs and the maintenance costs. As an example, in the case studies of this paper, the fuel costs are calculated by using Eqs.22-24.

$$x_{k,h} = \frac{P_{Gk,h}}{P_{Gk,\max}} \quad (22)$$

$$d_{k,h} = a x_{k,h}^2 - b x_{k,h} + c \quad (23)$$

$$M_{1,k} = \sum_h d_{k,h} \times P_{Gk,h} \times 0.9317 \text{ (l/kg)} \times C_{mp} \quad (24)$$

where  $x_{k,h}$  is the hourly generating factor of the  $k^{\text{th}}$  unit at hour  $h$ ;  $P_{Gk,h}$  (kW) and  $P_{Gk,\text{max}}$  (kW) are the corresponding hourly power output and the maximum power output of the unit,  $d_{k,h}$  (kg/kWh) is the hourly fuel consumption;  $a$ ,  $b$ , and  $c$  are the constants associated with the characteristics of the generating unit.  $M_{1,k}$  (\$) is the fuel cost of the  $k^{\text{th}}$  unit over the period considered, and  $C_{mp}$  (\$/l) is the fuel-oil price per liter in the market. In this paper, we use  $C_{mp}$  of 0.248 (US\$/l). The variable maintenance cost,  $M_{2,k}$ , are calculated for different generating units. The variable cost of the SOGUs,  $C_j^{\text{SOGUs}}$  is thus the sum of  $M_{1,k}$  and  $M_{2,k}$ .

$$C_j^{\text{SOGUs}} = M_{1,k} + M_{2,k} \quad (25)$$

The SOGUs studied in this paper are the heavy-oil-fired generators. The maximum output power of each generator is 8 MW, with zero minimal power output and fast ramping rate within 30 sec to start up and shut down. Compared with the generating cost, the start-up and shutdown costs of the SOGUs studied are relatively small and are neglected in this paper. The minimal up-time and down-time of the SOGUs are also negligible as compared to the load interval (one sample load per 15 minutes) and are thus not considered in the paper. The start-up and shutdown costs as well as the minimal up-time and down-time constraints of the SOGUs can be easily integrated in the model, if they are significant for the other types of SOGUs.

Suppose the consumer has the possibility of selling its excess energy, the revenues obtained can be calculated by

$$R_s = E_s \times C_s \quad (26)$$

where  $E_s$  is the sold excess energy generated by the SOGUs in MWh, and  $C_s$  is the unit price (\$/MWh) for the transaction.

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## Author Introduction



**Hong-Tzer Yang** (M'02, SM'08) received the B.S. and M.S. degrees in electrical engineering from National Cheng-Kung University, Tainan, Taiwan, in 1982 and 1984 respectively, and received the Ph.D. degree in electrical engineering from National Tsing-Hua University, Hsin-Chu, Taiwan, in 1989. He chaired IEEE PES Taipei Chapter in 2002 and was the Director of Incubation Center, CYCU in 2000-2003 and the Chair of the Department of Electrical Engineering, CYCU in 2002-2004. In 2007, he joined the faculty of the Department of Electrical Engineering, NCKU as a professor.



**Pai-Chun Peng** was born in Miao-Li, Taiwan, R.O.C, on Jan. 1, 1980. He received the B.S. degree from the Department of Electrical Engineering at Feng Chia University, Tai-Chung, Taiwan, in 2002 and the M. S. degree from the Department of Electrical Engineering at CYCU in 2004, where he is currently pursuing his Ph. D degree. His research interests include economics, electric power

generation, evolutionary programming, and power system  
planning.